Design and Testing of Access-Tube TDR Soil Water Sensor

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Abstract. *We developed the design of a waveguide on the exterior of an access tube for use in time-domain reflectometry (TDR) for in-situ soil water content sensing. In order to optimize the design with respect to sampling volume and losses, we derived the electromagnetic (EM) fields produced by a TDR sensor with this geometry. Using this analytical derivation, the effects on sampling area and waveform shape of varying geometry and soil water content were examined. The theoretical results were compared to laboratory measurements of different design variations in air, triethylene glycol, deionized water, sand, and clay in order to evaluate sensor performance and model accuracy. Both theoretical results and lab measurements indicated a positive, though not strong, relationship between electrode separation distance and (EM) field penetration into the soil or other medium with which sensor prototypes were surrounded. Results indicated good correspondence between the hybrid mode EM model predictions and measurements, indicating the value of the hybrid mode analysis. The relationship between measured pulse travel time and soil volumetric water content was quadratic rather than linear as in conventional TDR. Different quadratic calibration equations were obtained for sand and clay soils, indicating that soil-specific calibrations will be required for this design.*

Keywords. Electromagnetics, sensors, soil water content.

Introduction

Knowledge of soil water content in the root zone is vital for timely management of (irrigation) water available to crops. Scheduling irrigation to supply water to crops at near optimal or deficit conditions requires water content sensors with improved accuracies (Merriam, 1966; Evett et al., 2009). Many methods have been explored for sensing soil water content, including remotely by passive microwave sensing (Jackson et al., 1989) and in-situ by neutron thermalization, capacitance sensors, or time-domain reflectometry sensors (Evett et al., 2008). Neutron probes are relatively impractical due to the regulatory burden and the fact that they cannot be left unattended for data logging. Capacitance systems suffer inaccuracies due to soil conductivity, temperature effects and variations in response due to variations in soil structure (Mazahrih et al., 2008; Evett et al., 1995, 2009). Time domain reflectometry (TDR) uses the travel time of an electrical pulse sent down a waveguide surrounded by the medium to be measured (Topp, 1980). The reflected waveform and its first derivative (Fig. 1) are used to determine the travel time of the pulse, which is related to the soil dielectric permittivity, which in turn is related to the soil water content. Several TDR electrode designs have been explored including printed circuit board (Nissen et al., 1999), trifilar rod probes (Heimovaara, 1993), and cylindrical access-tube designs (Redman and deRyck, 1994).
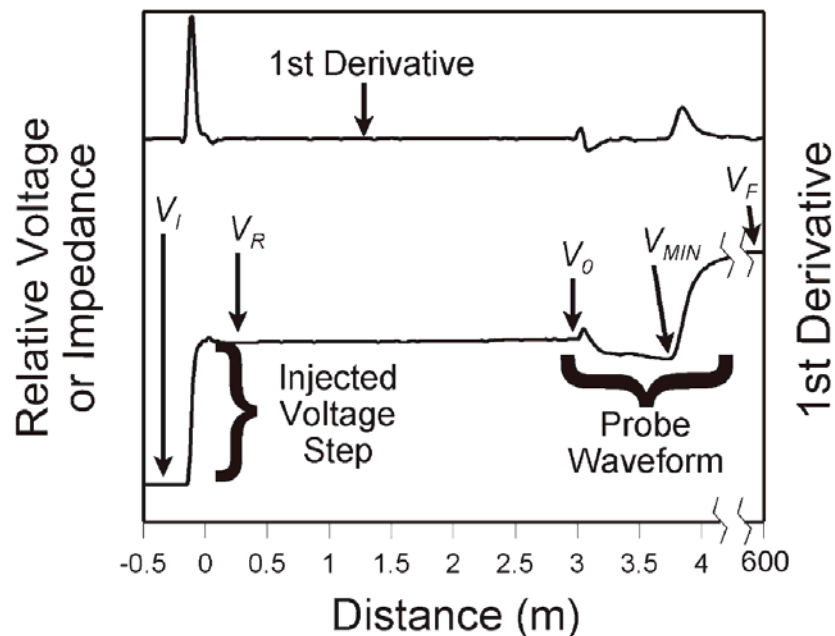

Figure 1. Plot of time domain reflectometer (TDR) waveform and first derivative as seen on a TDR waveform analysis computer program. The relative voltages are: V_I, the initial value; V_R, the value after the electrical pulse is injected inside the metallic time domain reflectometer; V_0, the value in the coaxial cable just before the TDR probe; V_{MIN}, the value at the lowest point in the part of the waveform that corresponds to the TDR probe; and V_F, the final value at maximum distance (approximately 600 m).

However, TDR sensing of soil water content presents three main problems. First, the dispersive nature of the soil medium distorts the transmitted waveform, usually a rectangular pulse. The

transmitted pulse has spectral content over a broad bandwidth. Since the permittivity of many soils are strongly frequency-dependent, and soil conductivity attenuates high-frequency components, the reflected waveform is distorted and is difficult to interpret (Hook and Livingston, 1995; Evett, 2000; Robinson et al., 2003). Second, probes that include some insulating dielectric material in contact with the conductive elements along their length, such as a waveguide on access tube design, measure a permittivity that is a combination of the soil permittivity and the permittivity of the probe body. The sampling area (volume) of the probe changes with the geometry of the waveguide electrodes and their relationship with the access tube, and it changes with the permittivity of the access tube material and that of the surrounding soil medium. This makes it difficult to translate the measured permittivity into a soil water content. Third, the soil medium is lossy, particularly at high frequencies, which can make waveform interpretation difficult. To overcome these difficulties, various approaches on the circuit side of the design could be considered, such as shorting diodes (Hook et al., 1992) or frequency-domain techniques (Friel and Or, 1999). Also, the sensor design could be optimized with respect to probe geometry.

For electromagnetic (EM) modeling of TDR probes, some have examined the probes as waveguides in theory, using the assumption of transverse EM (TEM) mode propagation (Knight et al., 1997), which allows estimation of sampling area in relation to probe geometry and the variation in the spatial distribution of the permittivity (Knight, 1992; Ferre et al., 1996; Ferre et al., 1998). However, TEM propagation is unrealistic for a TDR probe that incorporates some plastic coating or plastic substrate, due to the boundary conditions on continuous tangential field components at the material interfaces (Balanis, 1989). A mode that is applicable to the cylindrical access-tube design is the family of hybrid modes (Okamoto, 2006), which is the typical treatment for open-boundary rod waveguides such as fiber optic cables. The case of a hollow optical fiber was treated analytically in (Lee et al., 2009).

In this paper, we investigate a particular sensor design: a cylindrical non-conducting access tube with surface-mounted electrodes with their long axis oriented parallel to the long axis of the access tube (Fig. 2). The fields are first derived analytically, assuming hybrid mode propagation. Using the derived fields, and the soil dielectric model in Schwartz et al. (2009), the effects of probe geometry and soil water content on waveform shape and probe sensitivity to soil dielectric are estimated. For comparison, variations in the tube and electrode geometries are tested in different media, including air, triethylene glycol, deionized water, sand, and clay loam.
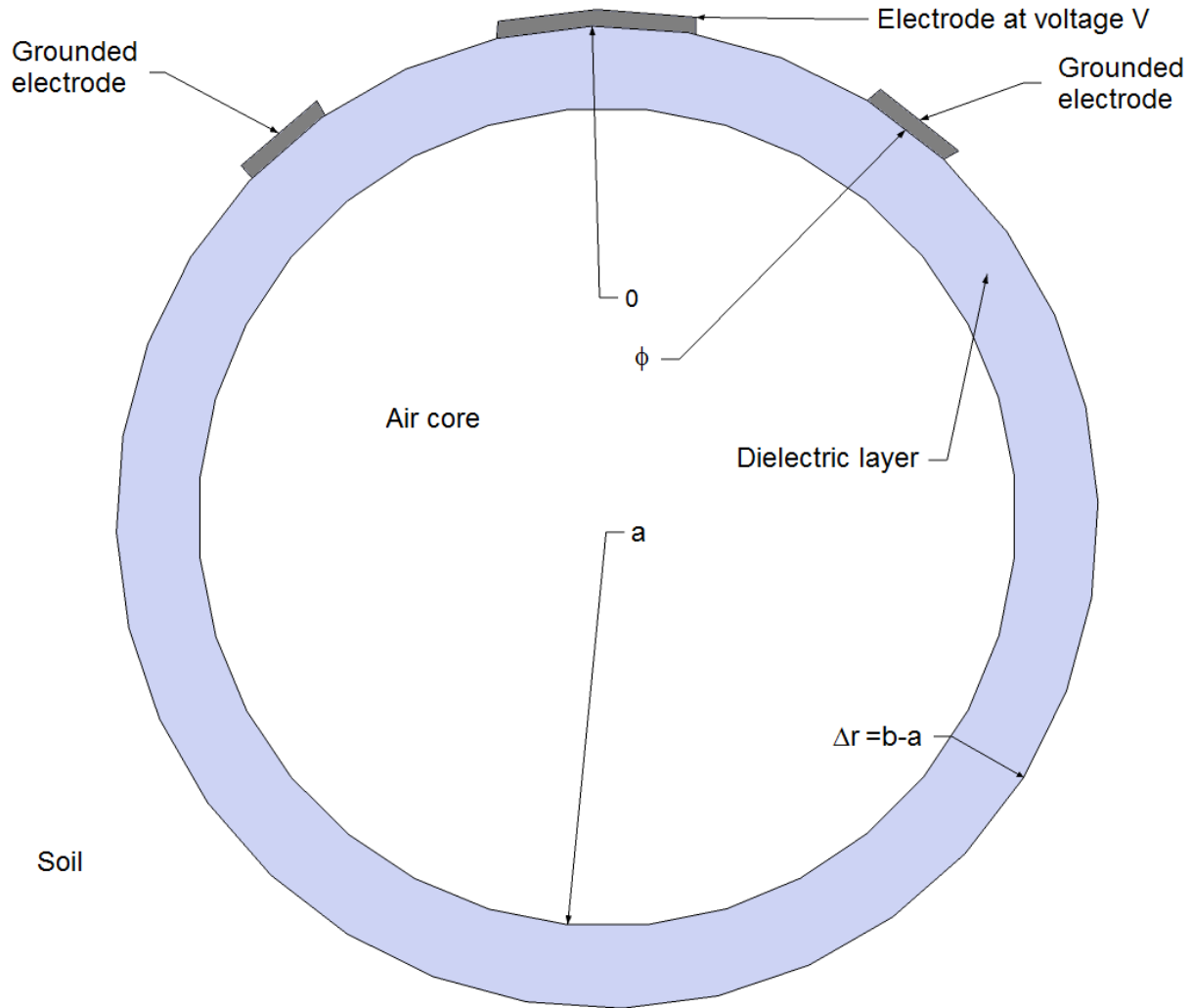
Figure 2. Waveguide on access tube TDR probe cross-section and parameterization showing the plastic access tube (dielectric layer) of given radial dimensions (*a* and *b*) and a three-electrode TDR waveguide with given angular separation (Φ) between the electrodes.

Theory

Maxwell's equations can be solved analytically using various degrees of simplifying assumptions. For all analytical solution techniques, boundary conditions and sources must be incorporated. The enforcement of boundary conditions results in a nonlinear, implicit characteristic equation, the solution of which yields the wavenumbers at each frequency (Balanis, 1989). The sources are incorporated by a using a Fourier-Bessel expansion (Pozar, 2009).

To make the problem analytically tractable, the derivation assumes conductors are perfect electric conductors of zero thickness, that the probe installation is such that there is no air gap between soil and sensor, and that (for purposes of solving for the wavenumber) the permittivity of the various media are purely real. The dielectric and conductive are used to estimate attenuation coefficients. The propagating EM fields are assumed to be the so-called "hybrid

modes," as seen in fiber optic cables, as opposed to the assumed TEM mode often used in previous TDR analyses. The TEM is in fact physically invalid for this type of waveguide above DC since it is incapable of meeting the boundary conditions.

Describing the fields in this fashion, and solving for the wavenumbers that propagate given the boundary conditions, the sensor performance can be predicted using two metrics. First, the sampling area, a measure of the field penetration into the soil, can be calculated using the estimated fields. Second, by solving for the wavenumbers at a range of frequencies, the waveforms in the time domain may be reconstructed using the discrete time Fourier transform.

The analytical development was implemented in MATLAB. Soil permittivity was calculated using the model of Schwartz (2009) and the permittivity of the plastic tube substrate was assumed homogeneous and frequency-invariant. The fields were calculated at points on a cylindrical mesh using the expressions for each of the field components, after solving the characteristic equation using the MATLAB built-in root-finding routines. The dominant mode is known as the HE11 mode (Lee et al., 2009). Plots of the real and imaginary components of the electric fields at 1GHz demonstrate the double-peaked intensity distribution of the HE11 mode in the access tube sensor (Fig. 3) (Lee et al., 2009). This isn't the same as the total fields, which also includes higher order modes, but most of the electromagnetic power is in this mode.
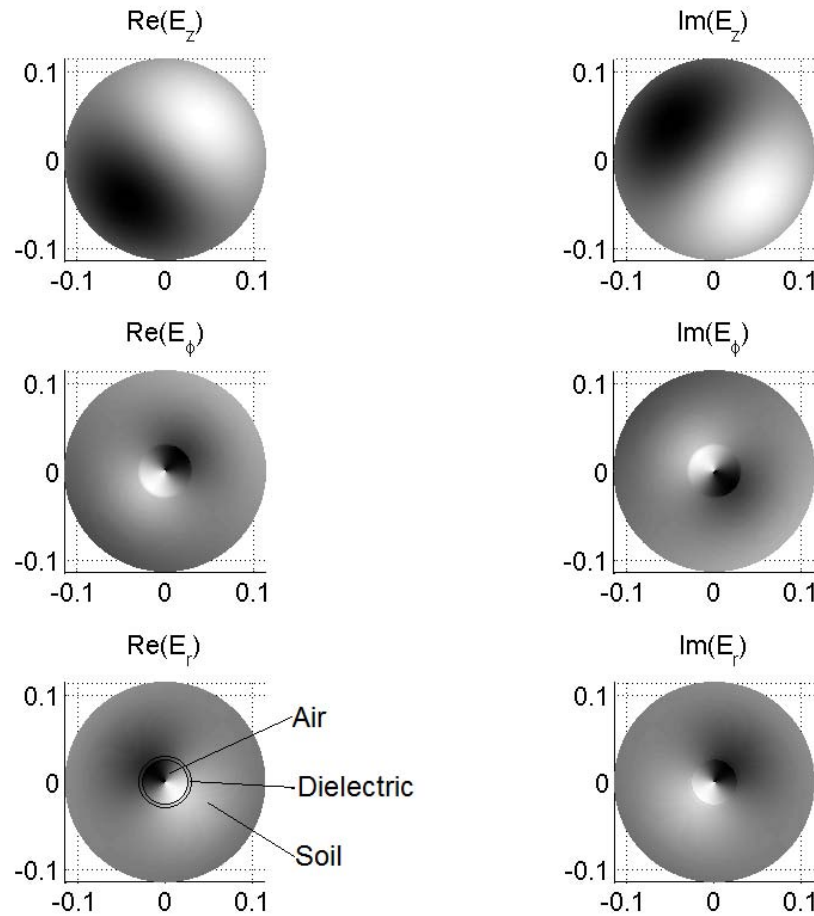

Figure 3. Electric field components of HE11 mode for an access tube TDR sensor in soil.

The MATLAB routines were used to investigate the impacts of the soil water content and sensor geometry on the sensor performance, in terms of the sampling area (a measure of the field penetration into the soil), the fraction of the total EM power in the soil, and the waveform. Several variables were investigated, including cylinder dielectric, cylinder thickness, and electrode width, but the primary impacts were from soil water content, cylinder radius, and electrode separation angle.

Measurement Methods and Materials

Seven sensor prototypes with different dimensions (Table 1) were tested in different media by comparing and analyzing waveforms acquired using a Tektronix 1502B cable tester and a microcomputer running the TACQ software (Evett, 2000). Waveforms were acquired using two time windows, one using a lower resolution of 251 points in 35 ns and another using a higher resolution of 251 points in 6 ns. The tests were conducted in four main groups. First, four waveforms of 251 points were acquired and averaged in standard media: air, triethylene glycol (at various degrees of dilution with deionized water), and deionized water; then, in sand or clay loam, mixed to achieve homogeneous moisture distribution, up to 0.20 m^3 m^{-3} volumetric water content, in increments of roughly 0.05 m^3 m^{-3}. The permittivity values of the standard media were taken as those determined with a standard trifilar probe and waveform analysis to estimate travel time and permittivity using TACQ. Soil was contained in a 0.203-m diameter, 0.216-m high PVC cylinder. Also, sensor prototypes were evaluated in sand or clay loam at or near saturation, achieved through introducing deionized water at the bottom of the packed column at a small positive pressure head. A calibrated load cell was used to weigh the column and determine the amount of water added. Sensor probe constants for bulk electrical conductivity calculations were determined by acquiring waveforms in KCl solutions of measured conductivity, using the relationship between reflection coefficient and conductivity described by Lin et al. (2008).

Table 1. Dimensions of sensor prototypes constructed and tested, where ID is inner diameter of the rigid white polyvinyl chloride access tube and OD is its outside diameter, ϕ (deg) is the angular separation between electrodes, Arc (mm) is the arc-wise distance between electrodes, and L is the electrode length.

Probe number	ID (mm)	OD (mm)	ϕ (deg)	Arc (mm)	L (m)
1	50.8	60.3	60	31.6	0.195
2	50.8	60.3	75	39.5	0.195
3	31.8	42.1	45	16.5	0.195
4	50.8	60.3	45	23.7	0.195
5	50.8	60.3	45	23.7	0.10
6	76.2	88.9	45	34.9	0.195
7	50.8	60.3	90	47.4	0.195

To evaluate sensor performance in soil, several metrics were employed. Waveforms were compared across sensors and media. Differences in probe response with respect to water content in sand and clay loam media were assessed using general linear models in SAS with a quadratic model and with probe design as a classification variable. In the triethylene glycol and deionized water tests, the TDR-estimated apparent permittivity values determined using the prototype sensors were compared to the actual permittivity as measured by a standard trifilar probe to give an indication of the probe's field penetration into the surrounding media. In the soils, the data were analyzed by comparing waveform slope at the second reflection. This gives a measure of waveform quality; higher slope indicates a less degraded waveform as the high frequency components of the input pulse are not attenuated as strongly, which should indicate smaller sampling area (volume). Thus, we hypothesized that an inverse relationship would exist between sampling area (A) and the slope of the second reflection.

Results

Simulations

From model estimates, the sampling area was smaller as soil water content increased (Figure 4a). Increasing access tube radius increased the electrode separation, which led to increased sampling area (Figure 4b). Increasing water content tended to decrease the slope of the second reflection (Fig. 5a), which indicates greater dispersive and conductive losses as would be expected from the permittivity model of Schwartz et al. (2009). For greater access tube radius, more dispersion in the waveform was simulated (Figure 5b). Increasing electrode separation angle increased sampling area very slightly (data not shown).
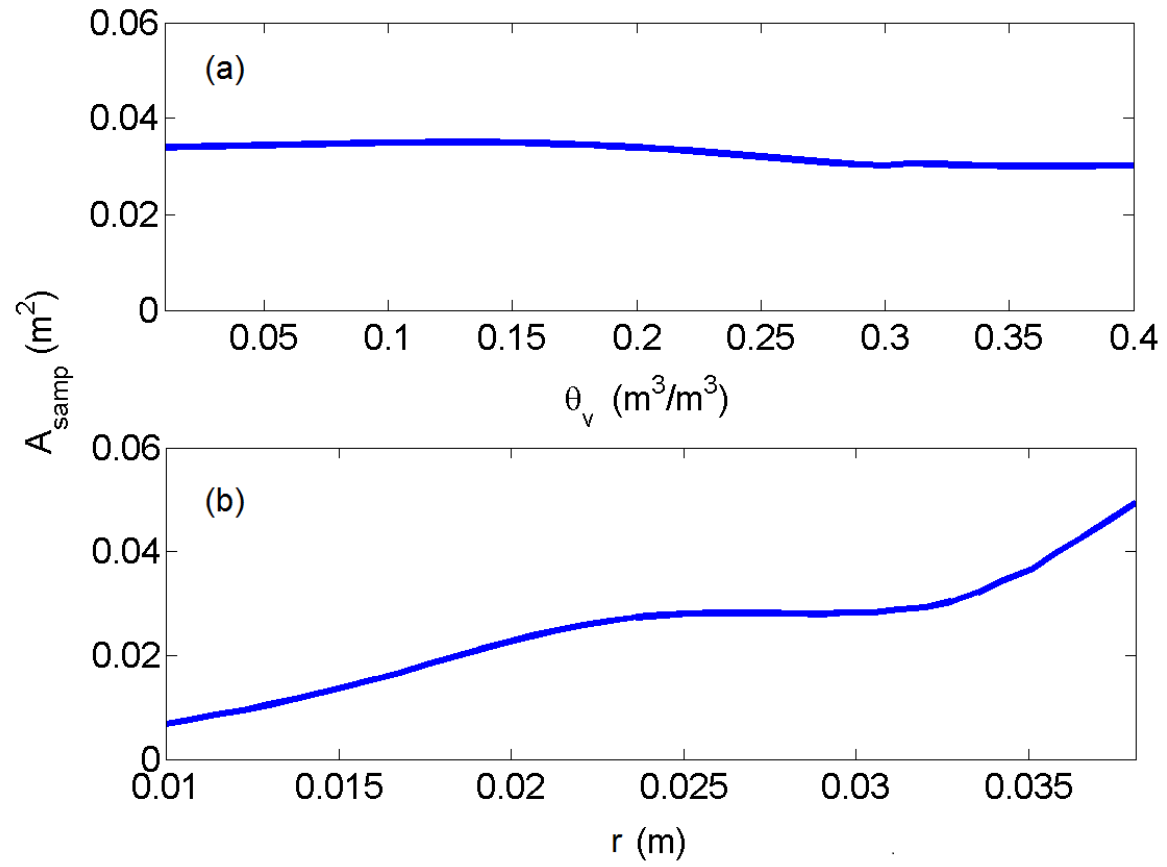
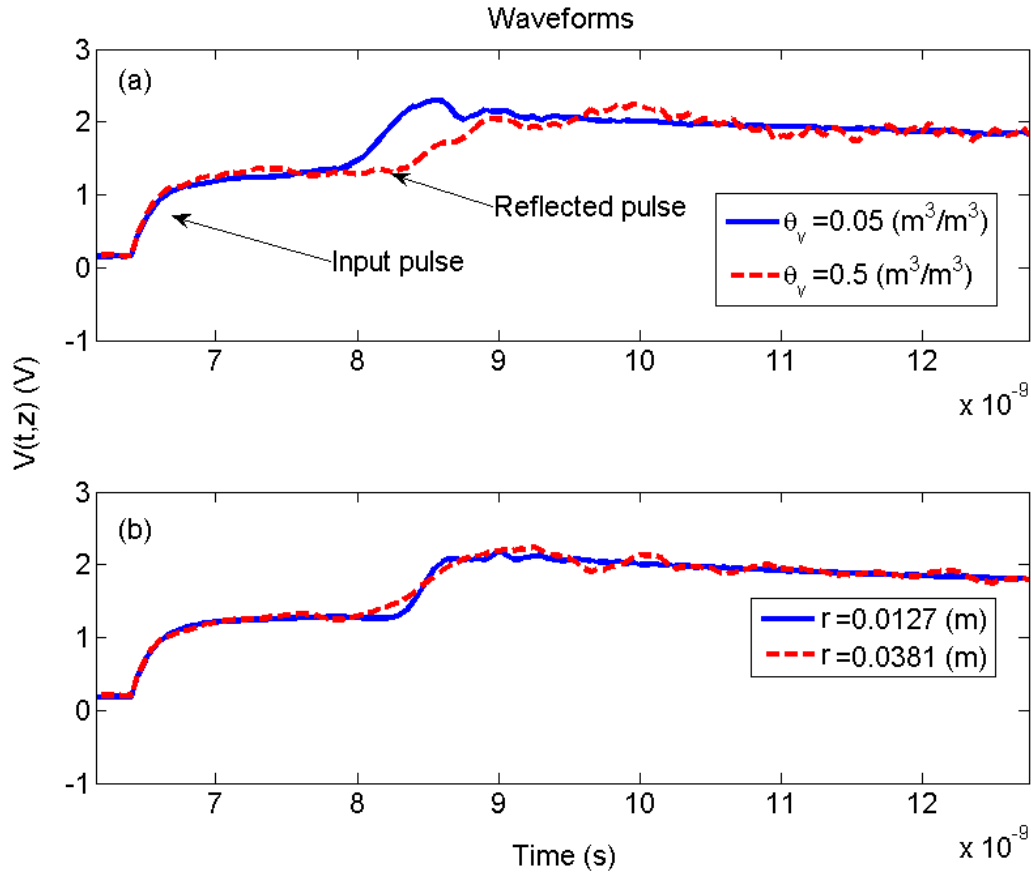Figure 4. Simulated sampling area (a) soil volumetric water content (θ_v); and (b) tube radius (r).

Figure 5. Simulated voltage (*V*) waveform at (a) two different soil water content (θ_v) values in a soil and (b) two different access tube radius values.

In sand, there were waveform differences among sensors (Fig. 6), which was not completely consistent with a nonsignificant (P=0.38) probe design effect on the quadratic response of travel time with respect to volumetric water content (Fig. 7a). Response of travel time to water content in the clay loam soil (Fig. 8) also had a significant (P<0.001) quadratic response (Fig. 7b); however the linear term was not significant (P=0.511).
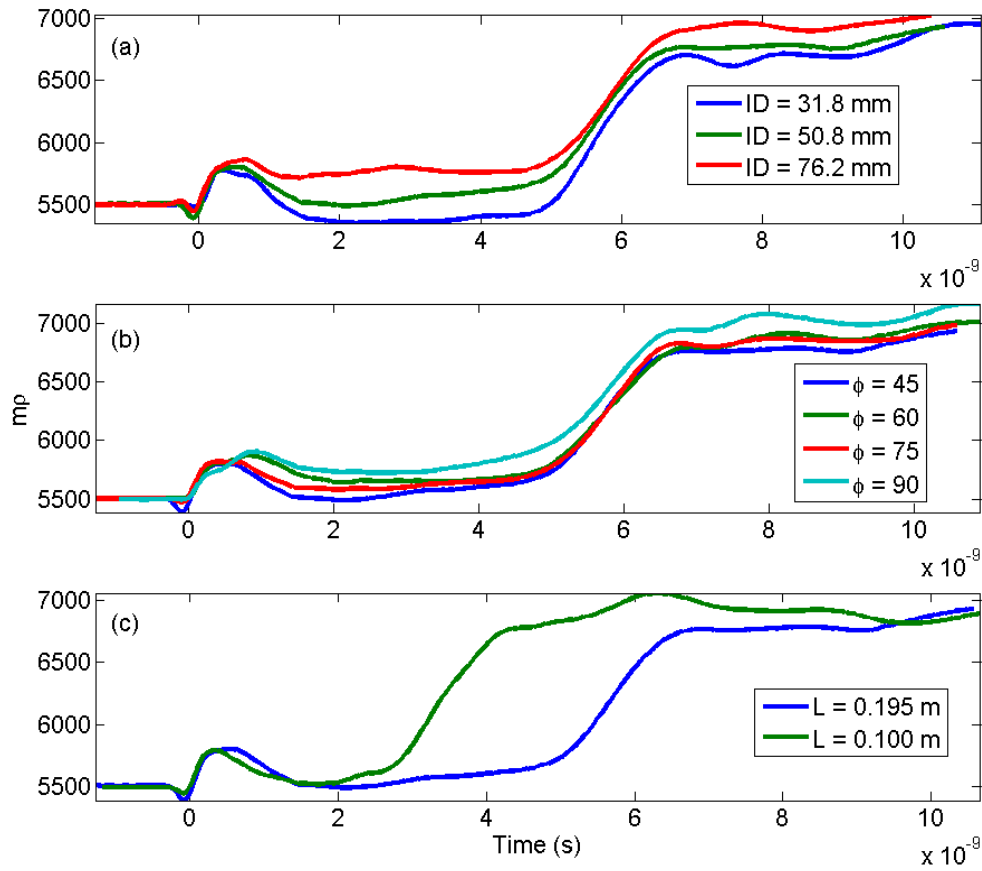
Figure 6. Waveforms at saturation in sand: (a) effect of changing access tube diameter (ID), while electrode length (*L*) is fixed at 0.195 m and electrode separation angle (ϕ) is fixed at 45°; (b) effect of changing ϕ, while *L* is fixed at 0.195 m and ID is fixed at 50.8 mm; (c) effect of changing *L*, while ϕ is fixed at 45 and ID is fixed at 50.8 mm.
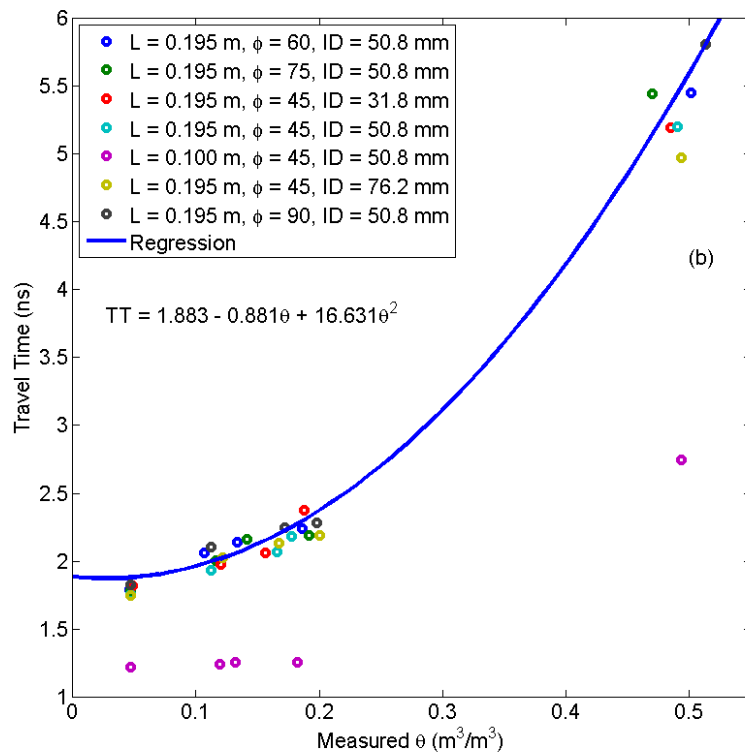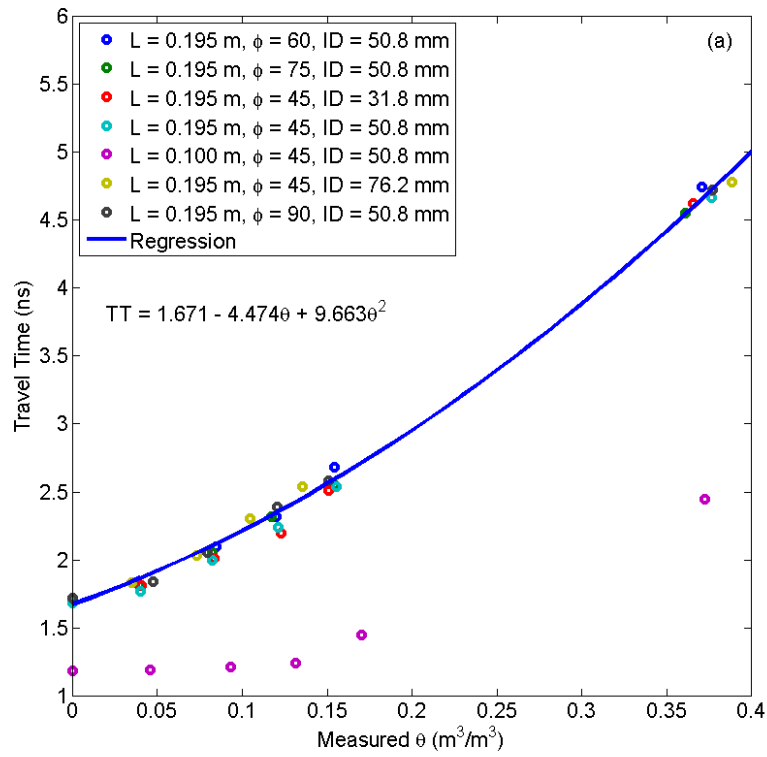
Figure 7. Relationships between measured volumetric water content (θ$_v$) and travel time, with

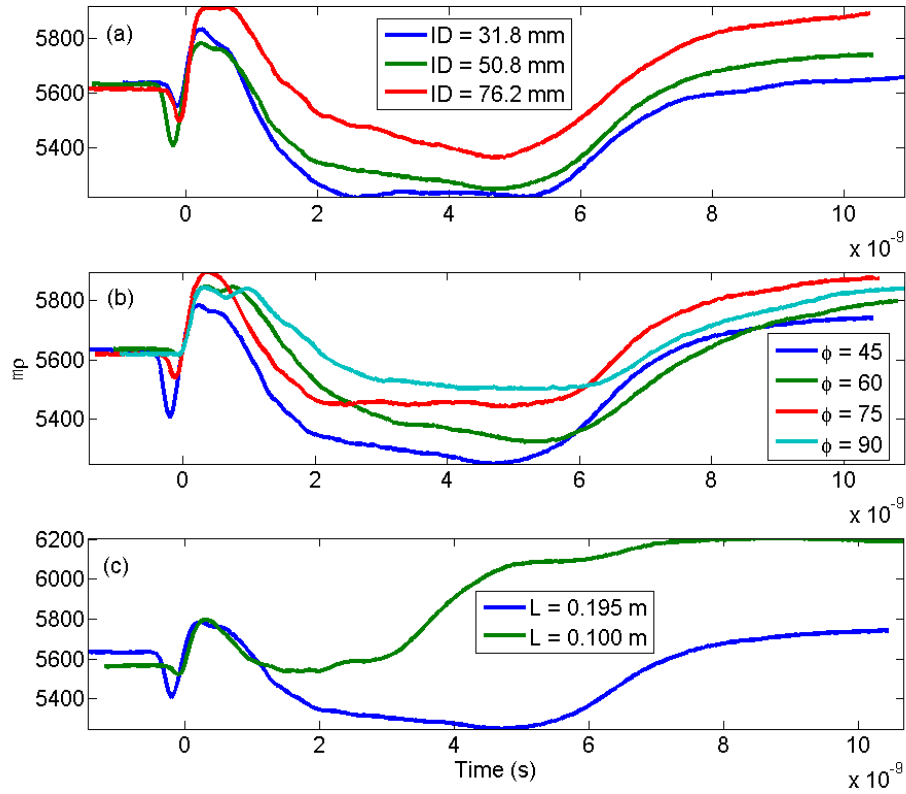quadratic regressions, in (a) sand and (b) clay.

Figure 8. Waveforms at saturation in clay: (a) effect of changing access tube diameter (ID), while electrode length (*L*) is fixed at 0.195 m and electrode separation angle (ϕ) is fixed at 45°; (b) effect of changing ϕ, while *L* is fixed at 0.195 m and ID is fixed at 50.8 mm; (c) effect of changing *L*, while ϕ is fixed at 45° and ID is fixed at 50.8 mm.

A lower probe constant indicates the probe has a greater sensitivity to DC soil conductivity. Calibrated probe constants ranged from 5 to 10 m^{-1} with increasing sensitivity to conductivity as electrode separation decreased (Fig 9a).

Comparing the TDR-estimated apparent permittivity to the known permittivity of fluids gives a measure of the field penetration into the media. Consequently, the ratio of measured permittivity to known permittivity would approach unity as the field penetration increases. The relationship between this ratio and electrode separation was examined by a linear regression (Fig. 9b), using the data from the triethylene glycol and deionized water tests. The slope of this regression was statistically significant (P = 0.0195) and positive, showing that field penetration increased with increasing electrode separation. However, the RMSE of regression was +/-0.045, the same order of magnitude as the change in measured ϵ/actual ϵ over the range of arc distances, indicating that a strong relationship is not clear.

The mean maximum slope of the waveform at the open termination reflection (maximum in the first derivative of the waveform just after Vmin in Fig. 1) decreased with arc distance between

electrodes in both sand and in clay loam (Fig. 9c,d). In sand, the slopes were greater than in the clay loam, as sandy soils have less high-frequency dielectric losses (Topp et al., 2000). These results indicate greater signal attenuation at high frequencies caused by dielectric relaxation mechanisms and associated with a greater field penetration into the soil for probes with greater electrode separation distance.

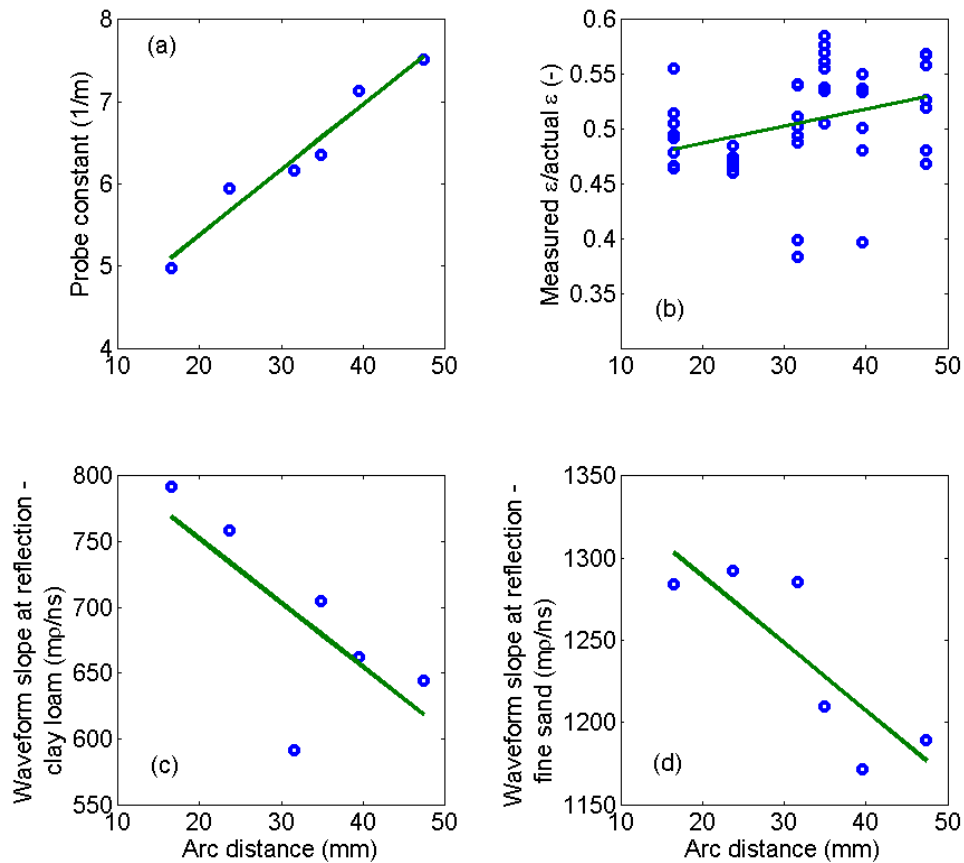Figure 9. Performance metrics versus electrode separation arc distance, with linear regressions: (a) probe constant, (b) measured ε/actual ε, and waveform slope $(m\rho\ ns^{-1})$ at second reflection in (c) clay loam and (d) in fine sand.

Conclusion

The performance of a cylindrical access-tube with surface mounted TDR probe electrodes was estimated using an analytical derivation of the so-called "hybrid" EM modes. Based on this analytical derivation, it was found that tube radius has a large impact on sampling area. The effects on waveform are greatest for soil water content and tube radius: where increasing any of these increase delay and dispersion.

Variations in the tube geometry were constructed and tested in different media, including air, triethylene glycol, deionized water, sand, and clay loam. Tests showed that increasing electrode separation resulted in increased field penetration into the surrounding media. Sensitivity to soil bulk electrical conductivity was greatest for prototypes having the smallest electrode separations, demonstrated by lower probe constants. These trends indicate that the propagating AC modes on the TDR are non-TEM, confirming the analytical derivation of hybrid mode propagation.

Acknowledgements

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